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High redshift Ly α emitters: clues on the Milky Way infancy

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ABSTRACT

With the aim of determining if Milky Way (MW) progenitors could be identified as high redshift Lyman Alpha Emitters (LAEs) we have derived the intrinsic properties of $z \approx 5.7$ MW progenitors, which are then used to compute their observed Ly α luminosity, L_α , and equivalent width, EW . MW progenitors visible as LAEs are selected according to the canonical observational criterion, $L_\alpha > 10^{42}$ erg s $^{-1}$ and $EW > 20$ Å. Progenitors of MW-like galaxies have $L_\alpha = 10^{39-43.25}$ erg s $^{-1}$, making some of them visible as LAEs. In any single MW merger tree realization, typically only 1 (out of ≈ 50) progenitor meets the LAE selection criterion, but the probability to have *at least* one LAE is very high, $P = 68\%$. The identified LAE stars have ages, $t_* \approx 150 - 400$ Myr at $z \approx 5.7$ with the exception of five small progenitors with $t_* < 5$ Myr and large $EW = 60 - 130$ Å. LAE MW progenitors provide $> 10\%$ of the halo very metal-poor stars $[Fe/H] < -2$, thus establishing a potentially fruitful link between high- z galaxies and the Local Universe.

Key words: cosmology: theory - galaxies: high redshift, evolution, stellar content, luminosity function - stars: formation, population II -

1 INTRODUCTION

Lyman Alpha Emitters (LAEs) are galaxies identified by means of a very strong Ly α line (1216 Å). Advances in instrument sensitivity and specific spectral signatures (strength, width and continuum break bluewards of the line) have enabled the confirmation of hundreds of LAEs in a wide redshift range, at $z \approx 2.25$ (Nilsson et al. 2008), $z \approx 3$ (Cowie & Hu 1998; Steidel et al. 2000; Matsuda et al. 2005; Venemans et al. 2007; Ouchi et al. 2008), $z \approx 4.5$ (Finkelstein et al. 2007), $z \approx 5.7$ (Malhotra et al. 2005; Shimasaku et al. 2006) and $z \approx 6.6$ (Taniguchi et al. 2005; Kashikawa et al. 2006).

LAEs have by now been used extensively as probes of both the ionization state of the intergalactic medium (IGM) and probes of high redshift galaxy evolution (Santos 2004; Dayal, Ferrara & Gallerani 2008; Nagamine et al. 2008; Dayal et al. 2009; Dayal, Ferrara & Saro 2010; Dayal, Maselli & Ferrara 2010). However, in spite of the growing data sets, there has been no effort to establish a link between the properties of these early galaxies to observations of the local Universe, *in primis* the Milky Way (MW). Our aim in this work is to investigate the possible connection between the Galactic building blocks and LAEs at a time when the Universe was ≈ 1 Gyr old. This will allow us to answer to questions

as: are the progenitors of MW-like galaxies visible as LAEs at high redshifts? How can we discriminate amongst LAEs which are possible MW progenitors and those that are not? What are the physical properties of these Galactic building blocks?

To this end, we adopt a novel approach of coupling the semi-analytical code **GAMETE** (Salvadori, Schneider & Ferrara 2007; Salvadori, Ferrara & Schneider 2008; Salvadori & Ferrara 2009), which traces the hierarchical build-up of the Galaxy, successfully reproducing most of the observed MW and dwarf satellite properties at $z = 0$, to a previously developed LAE model (Dayal, Ferrara & Gallerani 2008; Dayal et al. 2009; Dayal, Ferrara & Saro 2010), that reproduces a number of important observational data sets accumulated for high- z LAEs.

2 OBTAINING THE MW PROGENITORS

We start by summarizing the main features of **GAMETE**, which is used to build-up 80 possible hierarchical merger histories and to derive the properties of the MW progenitors at $z = 5.7^\dagger$. First, the possible hierarchical merger histories of

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† We specifically choose $z = 5.7$ for all our calculations as it represents the highest redshift for which a statistically significant sample of confirmed LAEs is available.

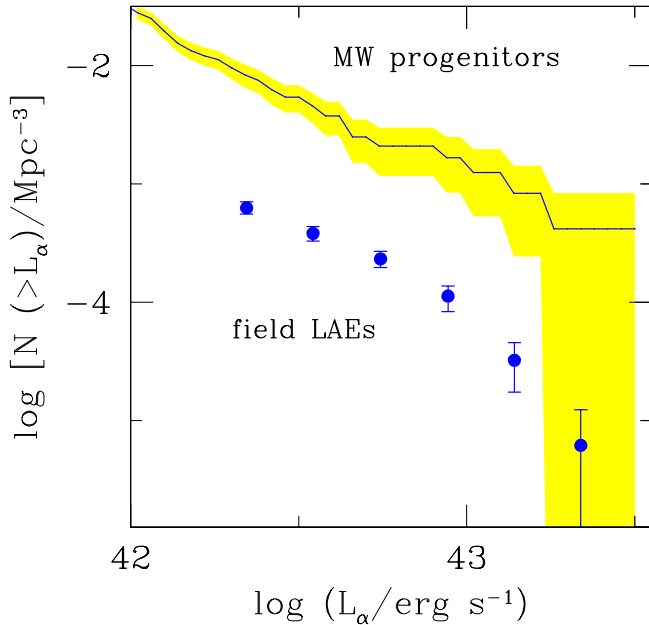


Figure 1. Cumulative Ly α luminosity function at redshift $z \approx 5.7$. The solid line shows the mean Ly α LF of the MW progenitors averaged over 80 realizations of the merger tree; the dashed area represents the $\pm 1\sigma$ spread among different realizations. For comparison only we show (points) the field LAE LF (Shimasaku et al. 2006).

a MW-size dark matter (DM) halo are reconstructed up to $z = 20$ via a Monte Carlo algorithm based on the extended Press-Schechter theory (see Salvadori, Schneider & Ferrara 2007 for more details). The evolution of gas and stars is then followed along each hierarchical tree by assuming that: (a) the initial gas content of DM haloes is equal to the universal cosmological value $(\Omega_b/\Omega_m)M_h$, where M_h is the DM halo mass, Ω_b (Ω_m) is the baryonic (DM) density parameter; (b) at any redshift, there exists a minimum halo mass to form stars, $M_{sf}(z)$, whose evolution accounts for the suppression of star formation (SF) in progressively more massive objects due to radiative feedback effects (see Fig. 1 of Salvadori & Ferrara 2009); (c) the gradual accretion of cold gas, M_c , into newly virializing haloes is regulated by a numerically calibrated infall rate (Kereš et al. 2005); (d) the SF rate, \dot{M}_* , is proportional to the mass of cold gas inside each galaxy, $\dot{M}_* = \epsilon_* M_c / t_{ff}$, where ϵ_* is the SF efficiency and t_{ff} the halo free fall time; (e) in halos with a virial temperature, $T_{vir} < 10^4$ K (minihalos), the SF efficiency is reduced as $\epsilon = \epsilon_* [1 + (T_{vir}/2 \times 10^4 \text{ K})^{-3}]^{-1}$ due to ineffective cooling by H_2 molecules. The chemical enrichment of gas, both in the proto-Galactic halos and in the MW environment is followed simultaneously by taking into account the mass-dependent stellar evolutionary timescales and the effects of mechanical feedback due to supernova (SN) energy deposition (see Salvadori, Ferrara & Schneider 2008 for more details).

The two free parameters of the model (star formation and wind efficiencies) are calibrated by reproducing the global properties of the MW (stellar/gas mass and metallicity) and the Metallicity Distribution Function (MDF) of Galactic halo stars (Salvadori, Schneider & Ferrara 2007, Salvadori, Ferrara & Schneider 2008); $M_{sf}(z)$ is fixed by matching the observed iron-luminosity relation for dwarf

spheroidal galaxies (Salvadori & Ferrara 2009). They are assumed to be the same for all progenitors in the hierarchical tree.

3 IDENTIFYING LAES

By using **GAMETE** we obtain the total halo/stellar/gas masses (M_h , M_* , M_g), the instantaneous SF rate (\dot{M}_*), the mass weighted stellar metallicity (Z_*) and the mass-weighted stellar age (t_*) of each MW progenitor, in each of the 80 realizations considered. These outputs are used to calculate the total intrinsic Ly α (L_α^{int}) and continuum luminosity (L_c^{int}) which include both the contribution from stellar sources and from the cooling of collisionally excited neutral hydrogen (H I) in the interstellar medium (ISM) (Dayal, Ferrara & Saro 2010).

The intrinsic Ly α luminosity can be translated into the observed luminosity such that $L_\alpha = L_\alpha^{int} f_\alpha T_\alpha$, while the observed continuum luminosity, L_c is expressed as $L_c = L_c^{int} f_c$. Here, f_α (f_c) are the fractions of Ly α (continuum) photons escaping the galaxy, undamped by the ISM dust and T_α is the fraction of the Ly α luminosity that is transmitted through the IGM, undamped by H I [‡].

The main features of the model used to calculate f_c , f_α and T_α are: (a) for each MW progenitor the dust enrichment is derived by using its intrinsic properties (\dot{M}_* , t_* , M_g) and assuming Type II supernovae (SNII) to be the primary dust factories. The dust mass, M_d , is calculated including dust production due to SNII (each SN produces $0.5M_\odot$ of dust), dust destruction with an efficiency of about 40% in the region shocked to speeds $\geq 100 \text{ km s}^{-1}$ by SNII shocks, assimilation of a homogeneous mixture of dust and gas into subsequent SF (astration), and ejection of a homogeneous mixture of gas and dust from the galaxy due to SNII. (b) Following the calculations presented in Dayal, Maselli & Ferrara (2010) for high- z LAEs, the dust distribution radius, r_d , is taken to scale with the gas distribution scale, r_g , such that $r_d \sim 0.5r_g$ [§] (c) f_c is calculated assuming a slab-like dust distribution and we use $f_\alpha = 1.3f_c$, as inferred for LAEs at $z \approx 6$. (d) T_α is calculated using the mean photoionization rate predicted by the Early Reionization Model (ERM, reionization ends at $z \approx 7$) of Gallerani et al. (2008), according to which the neutral hydrogen fraction $\chi_{\text{HI}} = 7 \times 10^{-5}$ at $z \approx 5.7$. Complete details of these calculations can be found in Dayal, Ferrara & Saro (2010) and Dayal, Maselli & Ferrara (2010).

Progenitors are then identified as LAEs based on the currently used observational criterion: $L_\alpha \geq 10^{42} \text{ erg s}^{-1}$ and the observed equivalent width, $L_\alpha/L_c \geq 20 \text{ \AA}$. We use a comoving volume of the Milky Way environment (30Mpc^3) to calculate the number density of the progenitors visible as LAEs and the observed LAE luminosity function (LF), shown in Fig. 1.

[‡] The continuum band (1250-1500 \AA) is chosen so as to be unaffected by H I absorption.

[§] the gas distribution radius is calculated as $r_g = 4.5\lambda r_{200}$, where the spin parameter, $\lambda = 0.05$ (Ferrara, Pettini & Shchekinov 2000) and r_{200} is the virial radius.

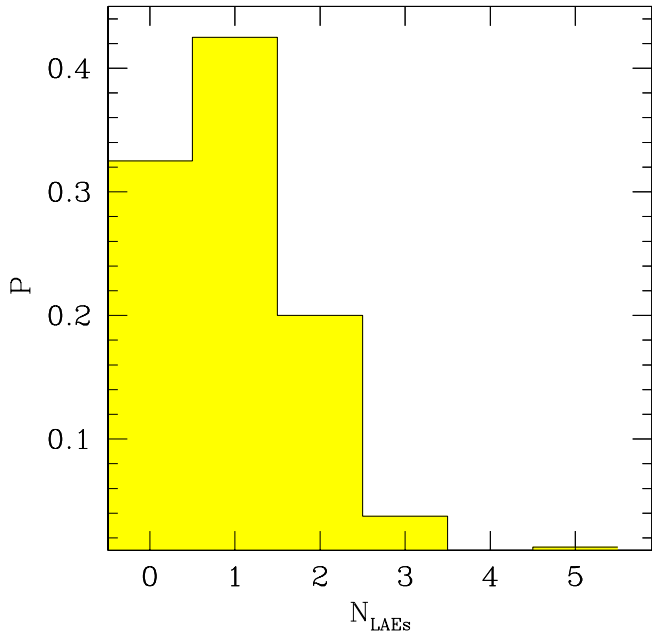


Figure 2. Probability of finding a number, N_{LAEs} , of LAEs in a single MW realization, averaged over 80 hierarchical merger histories at $z \approx 5.7$.

4 RESULTS

We start by comparing the number density of field LAEs observed at $z \approx 5.7$ with the average LF of the Milky Way progenitors at the same epoch (Fig. 1). The number density of MW progenitors decreases with increasing Ly α luminosity, reflecting the higher abundance of the least massive/luminous objects in Λ CDM models. The MW progenitors cover the entire range of observed Ly α luminosities, $L_\alpha = 10^{42-43.25} \text{ erg s}^{-1}$. We then conclude that *among the LAEs observed at $z \approx 5.7$ there are progenitors of MW-like galaxies*. For any given L_α the number density of MW progenitors is higher than the observed value because the MW environment is a high-density, biased region. As discussed in the final Section, uncertainties on the treatment of dust may also play a role.

In Fig. 2 we show the probability distribution function (PDF), P , of finding a number N_{LAEs} of LAEs in any given MW realization. The PDF has a maximum ($P = 0.42$) at $N_{\text{LAEs}} = 1$; while in any single MW realization, there are ≈ 50 star-forming progenitors with stellar masses $M_* \gtrsim 10^7 M_\odot$, on average only one of them would be visible as a LAE. We note that $P = 0.32$ for $N_{\text{LAEs}} = 0$, while it rapidly declines ($P < 0.2$) for $N_{\text{LAEs}} > 1$. We conclude that the MW progenitors that would be observable as LAEs at $z \approx 5.7$ are rare ($\approx 1/50$), but the probability to have *at least* one LAE in any MW hierarchical merger history is very high, $P = 68\%$.

Let us now consider the physical properties of the building blocks of the MW. \dot{M}_* represents the dominant physical factor to determine whether a progenitor would be visible as a LAE, since it governs the intrinsic Ly α /continuum luminosity, the dust enrichment (and hence absorption) and T_α , as both the size of the ionized region around each source and the H I ionization fraction inside it scale with \dot{M}_* (Dayal, Ferrara & Gallerani 2008). This implies the existence of a

SF rate threshold for MW progenitors to be visible as LAEs which is $\dot{M}_*^{\text{min}} \approx 0.9 M_\odot \text{ yr}^{-1}$ (panel (a) of Fig. 3). Since $\dot{M}_* \propto M_g$ (see Sec. 2), such a lower limit can be translated into a threshold gas mass: $M_g^{\text{min}} \approx 8 \times 10^7 M_\odot$ (panel (b)). In turn, the gas content of a (proto-) galaxy is predominantly determined by the assembling history of its halo and the effects of SN (mechanical) feedback. While the most massive MW progenitors ($M_h > 10^{10} M_\odot$) display a tight $M_g - M_h$ correlation, the least massive ones are highly scattered, reflecting the strong dispersion in the formation epoch/history of recently assembled halos (panel (b)). As a consequence, *LAEs typically correspond to the most massive progenitors of the hierarchical tree*, i.e. the major branches (black points in the panels). In particular, we find that *all* haloes with $M_h \geq 10^{10} M_\odot$ (40 haloes) are LAEs. At decreasing M_h , instead, the progenitors can be visible as LAEs only by virtue of a high gas mass content or extremely young ages; there are 5 such objects, with $M_h \approx 10^9 M_\odot$, as seen from panel (b).

By comparing the panels (b) and (c) of Fig. 3, we can see that M_d of the Galactic building blocks closely tracks M_g . Since the gas mass content of the $z \approx 5.7$ MW progenitors is reduced by ≈ 1 order of magnitude with respect to the initial cosmic value, due to gas (and dust) loss in galactic winds, their resulting dust mass is relatively small: $M_d \approx 10^{4-5.7} M_\odot$. As a consequence all the progenitor galaxies have a color excess $E(B-V) < 0.025$. In panel (d) we see that as expected, $E(B-V)$ increases with M_* , i.e. more massive galaxies are redder. However the trend is inverted for $M_* < 10^8 M_\odot$; even though the dust masses in these low mass objects ($M < 10^9 M_\odot$) is $M_d \lesssim 10^{4.2} M_\odot$, due to their small virial radius, both the gas distribution scale, and hence the dust distribution scale are very small (see Sec. 3). The concentration of the dust in a small area leads to a large dust attenuation and hence, a large value of the color excess.

MW progenitors visible as LAEs are generally intermediate age objects, $t_* \approx 150 - 400$ Myr, as seen from panel (e); the largest progenitors tend to be the oldest ones, an expected feature of standard hierarchical structure formation scenarios. However, the ages show a large scatter, especially at decreasing M_* , reflecting the great variety of assembling (and SF) histories of recently formed halos. Interestingly the five $M_h \approx 10^9 M_\odot$ newly formed ($z < 6$) progenitors visible as LAEs have a very young stellar population, $t_* \leq 5$ Myr. The high \dot{M}_* induced by the large mass reservoir and the copious Ly α production from these young stars makes them detectable.

In panel (f) we can see that these newly virializing galaxies are metal-poor objects, with an average stellar metallicity $Z \approx 0.016 - 0.044 Z_\odot$. As these galaxies host a single and extremely young stellar population, such low Z value reflects the metallicity of the MW environment at their formation epoch, $z \approx 5.7$ (see the middle panel in Fig. 1 of Salvadori, Ferrara & Schneider 2008). The more massive MW progenitors visible as LAEs, instead, are more metal rich, $Z \approx 0.3 - 1 Z_\odot$; their intermediate stellar populations form during a long period (see Fig. 4) and from a gas that is progressively enriched by different stellar generations.

The fact that the physical properties of the LAEs progenitors obtained with our model are consistent with those inferred from the observations of field LAEs (Fig. 3) is a notable success of our model.

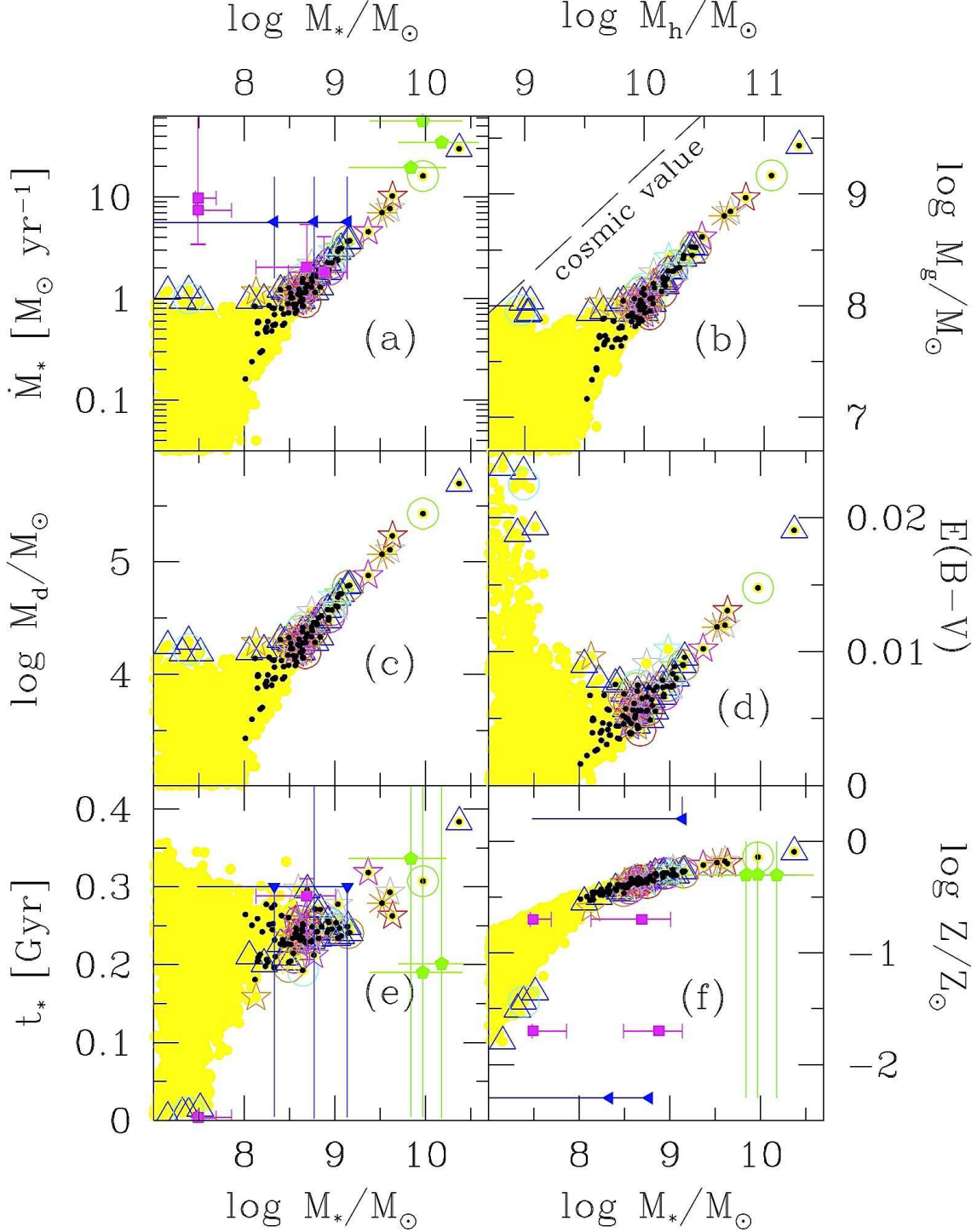


Figure 3. Physical properties of $z \approx 5.7$ MW progenitors in 80 different hierarchical merger histories. We show: (i) all the progenitors (yellow circles), (ii) the major branches of each hierarchical tree (black filled points) and (iii) the progenitors identified as LAEs (colored open symbols). LAEs pertaining to the same (different) realizations are shown with the identical (different) colored symbols (see the text and Fig. 2). Triangles are used for those realizations in which there is only one LAE. As a function of the total stellar mass M_* the various panels show: (a) the instantaneous star formation rate, \dot{M}_* ; (c) the dust mass, M_d ; (d) the color excess $E(B-V)$; (e) the average stellar age, t_* ; (f) the average stellar metallicity Z . Panel (b) shows the relation between the halo and gas mass, with the cosmic value $(\Omega_b/\Omega_m)M_h$ pointed out by the dashed line. Points with errorbars are the observational LAE data collected by Ono et al. 2010 (magenta squares, 1 LAE, four different models), Pirzkal et al. 2007 (blue triangles, 3 LAEs) and Lai et al. 2007 (green circles, 3 LAEs).

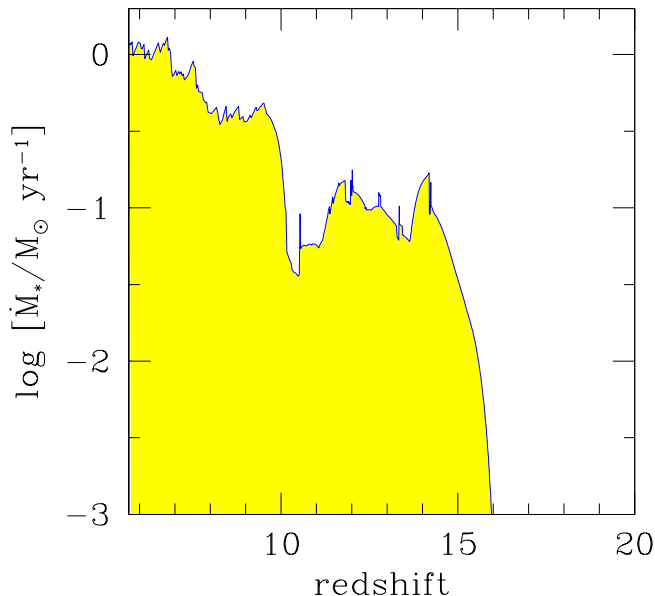


Figure 4. Star formation history of a typical MW progenitor identified as a LAE at $z \approx 5.7$.

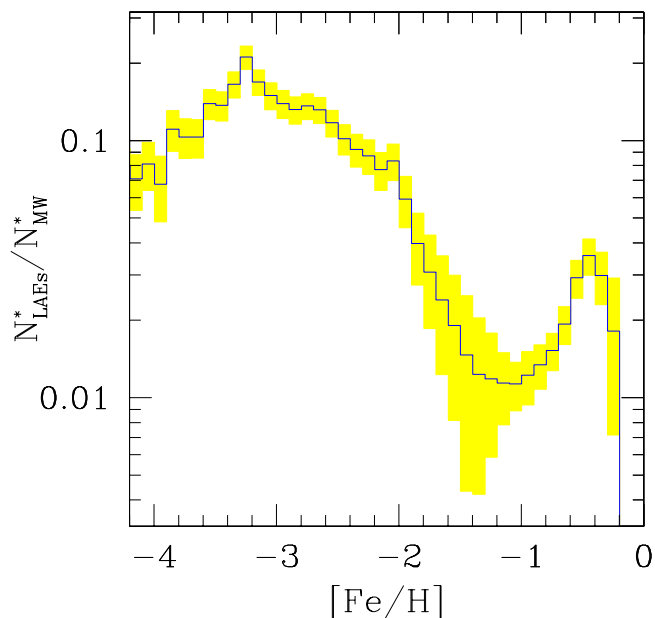


Figure 5. Fraction of LAE MW halo relic stars as a function of their iron abundance. The histogram shows the average fraction among 80 realizations of the hierarchical tree; the shaded area shows the $\pm 1\sigma$ dispersion among different realizations.

As mentioned above, the scatter in the LAE ages originates from different assembling and SF histories (SFH) of the MW progenitors. This can be better understood by considering the SFH of a typical[¶] MW progenitor identified as a LAE, as shown in Fig. 4. We find that since most LAEs typically correspond to the major branch, their progenitor seeds

[¶] We define as “typical” a LAE whose properties match the average values: $M_h \approx 10^{10} M_\odot$, $M_g \approx 10^8 M_\odot$, $\dot{M}_* \approx 2.3 M_\odot/\text{yr}$, $t_* \approx 230$ Myr.

are associated with high- σ peaks of the density field virializing and starting to form stars at high redshifts ($z \approx 16$). The SF rapidly changes in time, exhibiting several bursts of different intensities and durations, which follow merging events refueling gas for SF. During the “quiet” phase of accretion, instead, SN feedback regulates SF into a more gentle regime. The duration and intensity of the peaks depends on the effectiveness of these two competitive physical processes. At high redshifts ($z > 10$) the peaks are more pronounced because (i) the frequency of major merging is higher and (ii) mechanical feedback is stronger given the shallower potential well of the hosting halos ($M \approx 10^{8.5} M_\odot$, Salvadori, Ferrara & Schneider 2008).

We finally turn to the last question concerning the contribution of old and massive progenitors seen as LAEs, to the very metal-poor stars ($[\text{Fe}/\text{H}] < -2$) observed in the MW halo. In Fig. 5 we show the fractional contribution of long-living stars from LAEs to the MDF at $z = 0$. LAEs provide $> 10\%$ of the very metal-poor stars; the more massive the LAE, the higher is the number of $[\text{Fe}/\text{H}] < -2$ stars they contribute. This is because such metal-poor stellar fossils form at $z > 6$ in newly virializing halos accreting pre-enriched gas out of the MW environment (see Salvadori, Schneider & Ferrara 2007 and Salvadori et al. 2010). By $z \approx 5.7$, many of these premature building blocks have merged into the major branch, i.e. the LAE. Because of the gradual enrichment of the MW environment, which reaches $[\text{Fe}/\text{H}] \approx -2$ at $z \approx 5.7$ (see Fig. 1 of Salvadori, Ferrara & Schneider 2008), most of $[\text{Fe}/\text{H}] > -2$ stars form at lower redshifts, $z < 5.7$, thus producing the drop at $[\text{Fe}/\text{H}] > -2$. Note also the rapid grow of $N_{\text{LAEs}}^*/N_{\text{MW}}^*$ at $[\text{Fe}/\text{H}] > -1$, which is a consequence of the self-enrichment of building blocks resulting from *internal* SN explosions.

5 CONCLUSIONS

We have linked the properties of high- z LAEs to the Local Universe by coupling the semi-analytical code **GAMETE** to a previously developed LAE model. According to our results the progenitors of MW-like galaxies cover a wide range of observed Ly α luminosity, $L_\alpha = 10^{39-43.25} \text{ erg s}^{-1}$, with L_α increasing with M_* (or, equivalently, M_h); hence some of them can be observed as LAEs. In each hierarchical merger history we find that, on average, *only one* star-forming progenitor (among ≈ 50) is a LAE, usually corresponding to the major branch of the tree ($M_h \approx 10^{10} M_\odot$). Nevertheless, the probability to have *at least* one visible progenitor in any merger history is very high ($P = 68\%$). Interestingly, we found that the LAE candidates can be also observed as dropout galaxies since their UV magnitudes are always $M_{UV} < -18$.

On average the identified LAE stars have intermediate ages, $t_* \approx 150-400$ Myr, and metallicities $Z \approx 0.3-1 Z_\odot$; an exception is represented by five newly formed galaxies, which are hosted by small DM halos, $M_h \approx 10^9 M_\odot$, which are yet visible as (faint) LAEs ($L_\alpha \approx 10^{42.05} \text{ erg s}^{-1}$) by virtue of their high star formation rate and extremely young stellar population, $t_* < 5$ Myr. The low metallicity of these young galaxies, $Z \approx 0.016 - 0.044 Z_\odot$, reflects that of the MW environment at their formation epoch. Although rare (5 out of 80 LAEs), these Galactic building blocks could be even

more unambiguously identified among the least luminous LAEs, due to their larger Ly α equivalent widths, $EW = 60\text{--}130\text{ \AA}$ with respect to those ($\approx 40\text{ \AA}$) shown by older LAEs^{||}. These small and recently virialized halos ($z_{\text{vir}} \lesssim 6$) could be the progenitors of Fornax-like dwarf spheroidal galaxies (see Fig. 1 of Salvadori & Ferrara 2009). By identifying these LAEs, therefore, it would be possible to observe the most massive dSphs of the MW system just at the time of their birth.

Uncertainties remain on the treatment of dust in calculating the LF and observed properties of the MW progenitor LAEs identified here, especially at the low luminosity end of the LF. Several aspects require additional study. As gas, metal and dust are preferentially lost from low mass halos, pushing the mass resolution of simulations to even lower masses would be important. Also, the amount of dust lost in SN-driven winds remains very poorly understood, an uncertainty that propagates in the evaluation of the continuum and Ly α radiation escaping from the galaxy. Finally, Ly α photons could be affected considerably by the level of dust clumping. It is unclear to what extent these effects may impact the visibility of LAEs, as discussed in e.g. Dayal, Ferrara & Saro (2010). Progress on these issues is expected when high-resolution FIR/sub-mm observations of LAEs with ALMA will become available in the near future (Finkelstein et al. 2009; Dayal, Hirashita & Ferrara 2010).

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^{||} Due to the low dust mass, $f_c = f_\alpha \approx 1$ for all the progenitors we identify as LAEs; the observed EW is solely governed by T_α , which leads $EW \approx 40\text{ \AA}$ for almost all LAEs, except those with $t_* \leq 10\text{ Myr}$.

^{**} <http://wiki.arcetri.astro.it/bin/view/DAVID/WebHome>